PROTECTING FIRE FIGHTERS EXPOSED IN ROOM FIRES, PART 2: PERFORMANCE OF TURNOUT COAT MATERIALS UNDER ACTUAL FIRE CONDITIONS

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Protecting Fire Fighters Exposed in Room Fires, Part 2: Performance of Turnout Coat Materials Under Actual Fire Conditions

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Abstract

Seven experimental fires varying in fire load were conducted in a simulated townhouse. Specimens of various current fire fighters turnout coat materials were exposed in the room of fire origin. The time at which conditions would become untenable for the fire fighter due to pain, as well as the time to second degree burn, were calculated. These times ranked the coat specimens in roughly the same order as the "Thermal Protection Performance" measured according to NFPA 1971-1986, especially if the heat in the room developed rapidly.

Introduction

The present National Fire Protection Association (NFPA) standard 1971-1986, *Protective Clothing for Structural Fire Fighting*[1] requires that turnout coat materials have a minimum "thermal protection performance" (TPP) value of 35. This means that they must withstand a square wave exposure of 84 kW/m^2 (2 cal/cm^2 s) (50/50 radiant/convective heat flux) for 17.5 seconds before the heat buildup on the inside of the coat would cause a second degree (2°) burn to the skin of the wearer (assuming direct contact of the turnout coat with the skin). Krasny, Huang, and Rockett[2] discussed the heat flux conditions measured in a series of room burns in which flashover occurred and compared them to the protection afforded by turnout coats conforming to this standard. The main conclusion was that, in most room fires in which flashover

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occurs, the turnout coats would protect the wearer from injury only for a few seconds. Moreover, considerations of mobility, weight, and comfort would make it difficult to increase the protection time by making the coats bulkier.

The present paper discusses the results of tests in which specimens of turnout coat materials differing in TPP were exposed in actual room fires of varying intensity and rate of heat buildup. The fires were conducted to provide data for models predicting heat, pyrolysis gas, and smoke movement in a simulated residential townhouse; this provided an opportunity to conduct realistic turnout coat exposure tests. Data from those tests are used in this paper to determine the thermal protection afforded by fire fighters' turnout coats against heat conditions encountered in a room fire as compared with the results of the NFPA thermal protection performance bench-scale test (TPP). Two sets of turnout coat specimens were studied. One set varied over a wide range of TPP values. The second set of three assemblies had similar TPPs, in spite of major differences in the characteristics of the materials used.

The tenability limits used in this work result from recent efforts in fire hazard modeling.[3,4] Those efforts combine the evaluation of the time/heat relationships which would cause pain and, subsequently, incipient 2° burn. ("2° burn" covers a variety of burn depths in the skin that can heal without a skin transplant; "3° burn" indicates the need for a skin transplant.) See Bukowski[3] for the relationship between time and the concentration of smoke and pyrolysis gases that would cause incapacitation and death.

Methods and Materials

Arrangements for the Fires

The layout of the townhouse and the locations of the heat, smoke, and gas analysis sensors are shown in Figure 1. The instrumentation and computer algorithms to analyze the data acquired by these instruments are described in a paper by Peacock, Davis, and Lee.[5] The walls in all rooms were covered with calcium silicate board to avoid rebuilding after each fire. There was no furniture in any of the rooms in four of the seven fires; in the remaining fires, the burn rooms were furnished as discussed below.

The burn room in which the turnout coat specimens were exposed is shown in Figure 2. There were two doors; the door from this room to the rest of the townhouse was always open during the tests, the door to the outdoors was open or closed, as described below. The locations of the heat sources in the room are also indicated in Figure 1.

The seven experiments were selected to provide a range of exposures for the turnout coat specimens, from small fires up to and including a

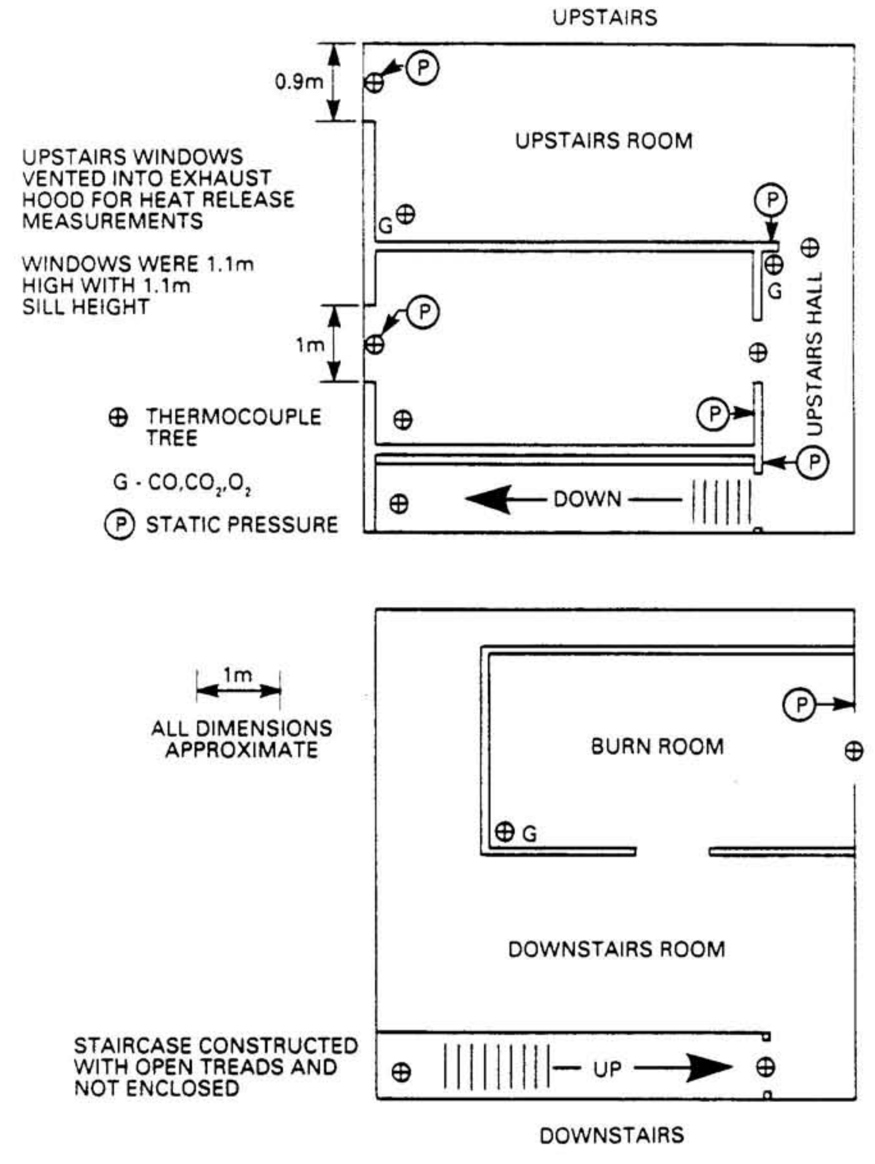

Figure 1. Layout and instrumentation of a simulated residential townhouse used for several full-size room fire tests.

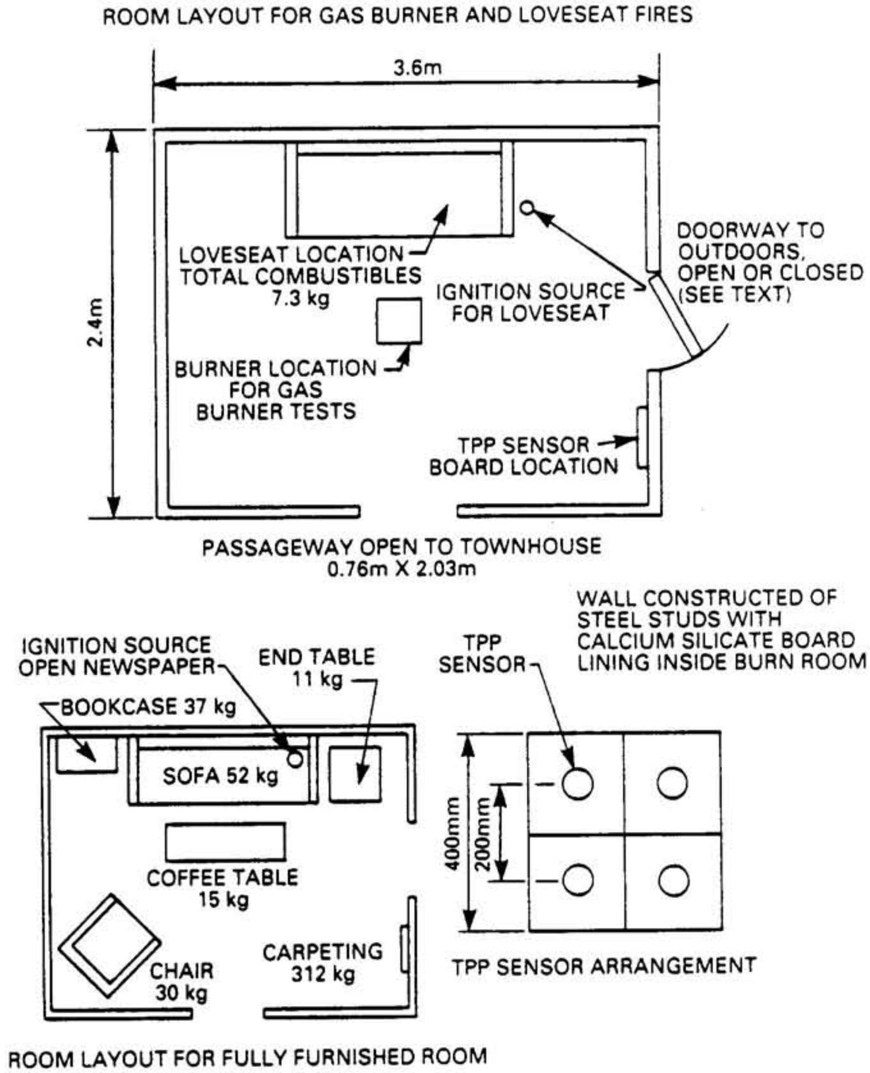

Figure 2. Test room layout and furnishings for several full-size room fire tests in a simulated residential townhouse.

fully involved room fire. In addition, both constant size and rapidly growing fires were included to assess the effect of the fire growth rate. The heat sources were:

1. approximately 300 and 500 kW natural gas fires of fifteen-minute duration (with about 20% of the energy supplied by acetylene, added to produce visible smoke); these fires provided data about heat and smoke movement for a rapidly rising and then constant, well-defined heat source; or
2. two loveseat mockups consisting of six polyurethane cushions (approximately 500 by 500 by 100 mm [20 by 20 by 4 in.]) covered with a polyolefin fabric and assembled in a steel frame; in these fires heat build-up was initially slower, but eventually much more severe than in the gas burner fires; or
3. a full complement of furniture as shown in Figure 2; this resulted in the most severe conditions.

For the loveseat and for the fully furnished room tests (the furnishing tests), ignition was accomplished with 100 ml of heptane contained in a 0.14 m diameter can on the floor to the side of the loveseat or sofa. This ignition source resulted in an approximately 10 kW fire for 5 minutes. Each of the gas fires and the love seat fires was run with the door open and with the door closed; the fully furnished fire was run with the door open.

For the measurement of the protective values of the turnout coat specimens, four of the heat sensors specified in NFPA 1971-1986[1] were mounted in a calcium silicate board. Three were covered with turnout coat assembly specimens as shown in Figure 2, the fourth was left bare to record the heat incident on the outside of the coat materials. The coat samples were approximately 100 by 100 mm. The sensors were copper discs 40 mm in diameter and 1.5 mm thick. The center of the sensor board was located about 500 mm from the floor and 500 mm from the front corner on the right wall. Four 32-gage type J thermocouples were attached to the back of the discs; their front was flush with the surface of the mounting block. The leads from the discs were covered with a high-temperature resistant, silicone gasketing material. The sensors were delivered with a calibration curve, and frequent recalibration between tests indicated that they maintained their characteristics during use. The curves produced by the sensors are shown in Figures 3 to 9. In preparing these figures, the raw data from the sensors were numerically smoothed.

Turnout Coat Specimens

The turnout coat assemblies are described in Table 1 and identified by

Table 1. Turnout coat assemblies.

Specimen:	T 53	T 33	T 38	T 41A	T 41B	T 39
Materials:						
Outer Shell	PBI/AR	AR	AR	AR	PBI/AR	AR
Moisture Barrier	PPTFE/AR	PPTFE/AR	PPTFE/AR	NCARNF	PPTFE/AR	NCCOT
Inner liner	RARQ	FRCOTFL	FRCOTDEN	NCARNF	ARQ	RARQ
Weight (g/m²)	710	765	900	1000	745	890
(oz/yd²)	21.0	22.5	26.5	29.5	22.0	26.0
Thickness (mm)	5.2	2.1	2.3	3.2	3.9	5.5
(mils)	207	83	95	125	155	215

PBI/AR—polybenzimidazole/aramid blend fabric
AR—aramid fabric
PPTFE/AR—moisture permeable fluorocarbon film/aramid fabric assembly
NCCOT—neoprene coated cotton fabric
NCARNF—neoprene coated aramid needle felt, serving both as a moisture barrier and an inner liner
RARQ—reprocessed aramid quilt with aramid fabric lining
ARQ—aramid quilt with aramid fabric lining
FRCOTFL—flame retardant treated cotton flannel
FRCOTDEN—flame retardant treated cotton denim

their TPP values. The first three assemblies were obtained first and were always exposed together. The second set was exposed in a later test series. It should be noted that there were different fire conditions in all seven room fires so that no replicate heat protection or room condition results were obtained under any single condition. The assembly listed in the first column had a very high TPP, with the second and third listed assemblies having considerably lower TPPs. The second set of three assemblies had similar TPPs, in spite of major differences in the characteristics of the outer shell, moisture barrier, and inner liner (also called thermal barrier) materials used. The total thickness and the total weight of the assemblies differed over a considerable range.

Results of Heat Exposure of Turnout Coat Specimens

Figures 3 to 9 show the heat per unit area as a function of time measured by the TPP sensors during the seven fires. As stated before, one of the sensors was exposed to the ambient conditions in the room, while three of the sensors were covered by various turnout coat assembly specimens. For each fire, the corresponding figure shows the heat/time relationships up to 100 kJ/m^2 (which provides an assessment of the injury potential of the exposure) and that for the total course of the fire (as an inset to the larger graph). Also shown on the figures is an estimate of the heat required to cause pain in an unprotected exposure. The pain and corresponding burn curves (used only to calculate time to burn) are based on a compilation[3] of all available data produced in this area by Stoll et al.[6,7] and by Derksen et al.[8] The present curve is an extension of that used in NFPA 1971 and Krasny et al.;[2] however, the differences are minor. The heat-per-unit-area/time, H (kJ/m^2), required to cause pain or burn is not a constant, but is a relatively slowly varying function of exposure time: for pain, $H = 26.8\, t^{0.26}$. For a 2° burn, $H = 54.7\, t^{026}$.

The exposure time, t, was used as a "tenability limit" for a protected fire fighter during a fire by determining the time at the intersection of the specimen exposure curves and the pain or 2° burn curve.

Description of Room Fires

Figures 3 to 9 indicate differences in the heat/time histories of the fires, as measured by the uncovered sensor. The four gas fires were cut off at 15 minutes; the loveseat and furnished room fires were permitted to burn to completion The initial slopes of the heat/time plots in the gas fires, Figures 3 to 6, were slightly lower when the door was closed than when it was open; however, during the later stages of the fires, the closed door resulted in more heat, as expected. The loveseat fires, Figures 7 and 8, increased in intensity slowly but started to build to a maximum at about 150 seconds with the door closed, and at about 200 seconds with

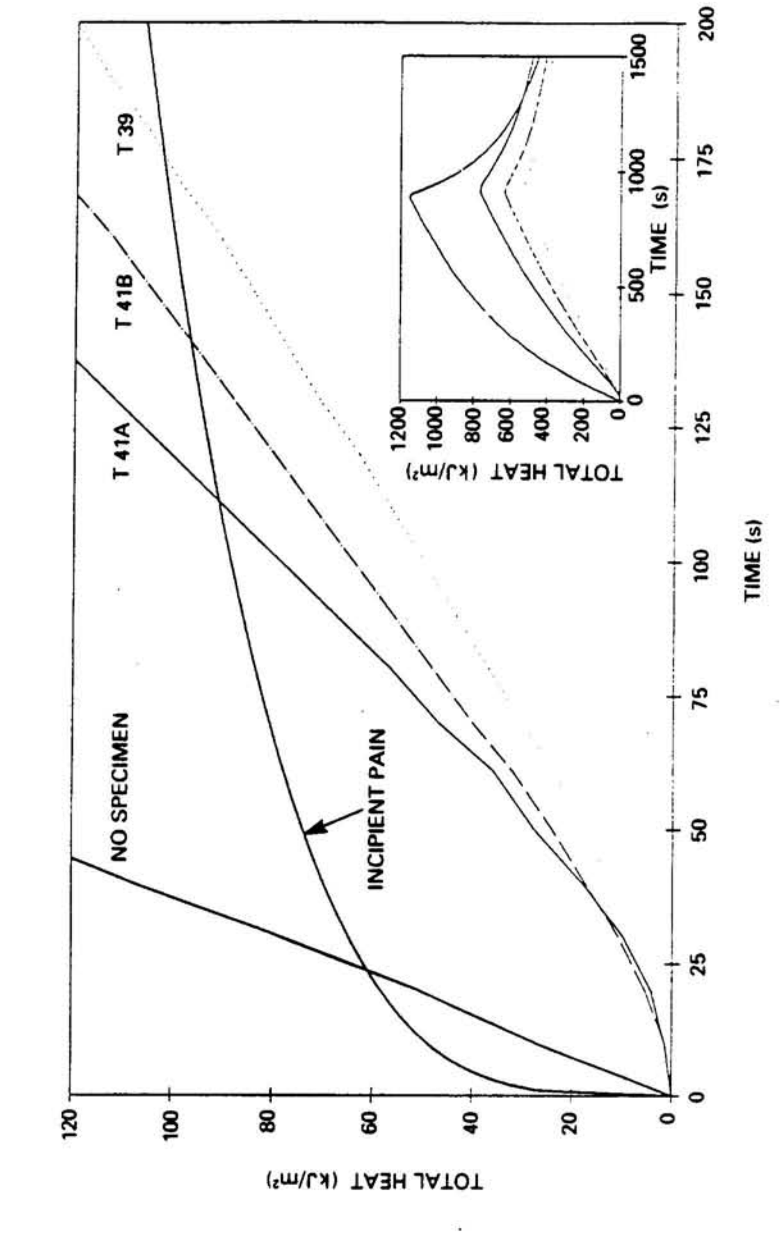

Figure 3. Total heat measured by the TPP sensors during a 300 kW gas burner fire with an open doorway.

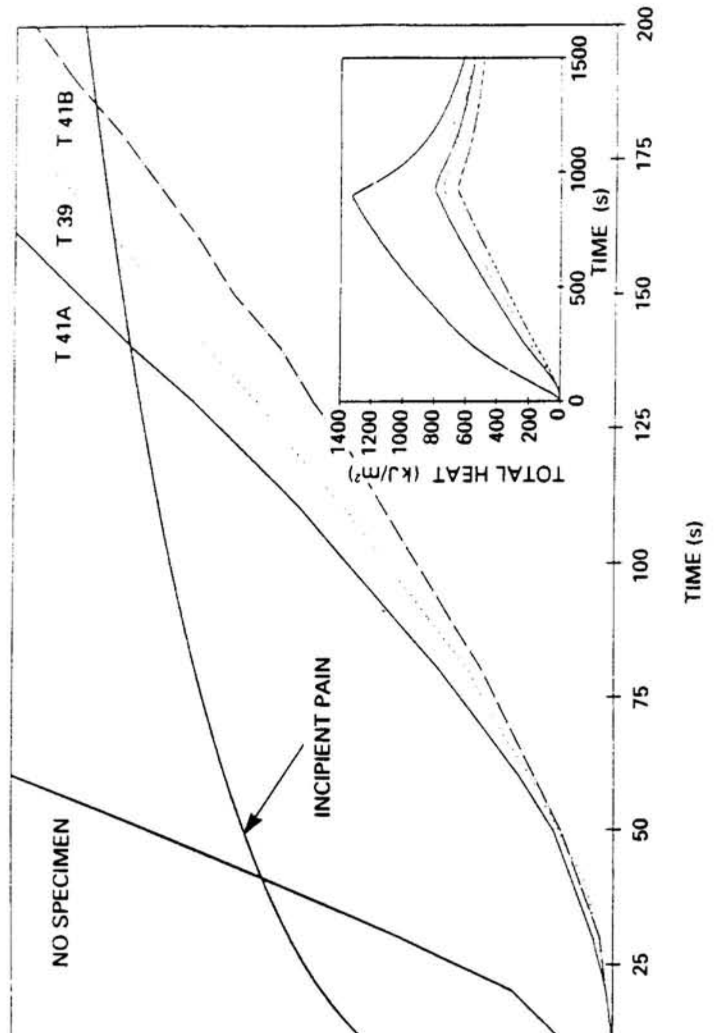

Figure 4. Total heat measured by the TPP sensors during a 300 kW gas burner fire with a closed doorway.

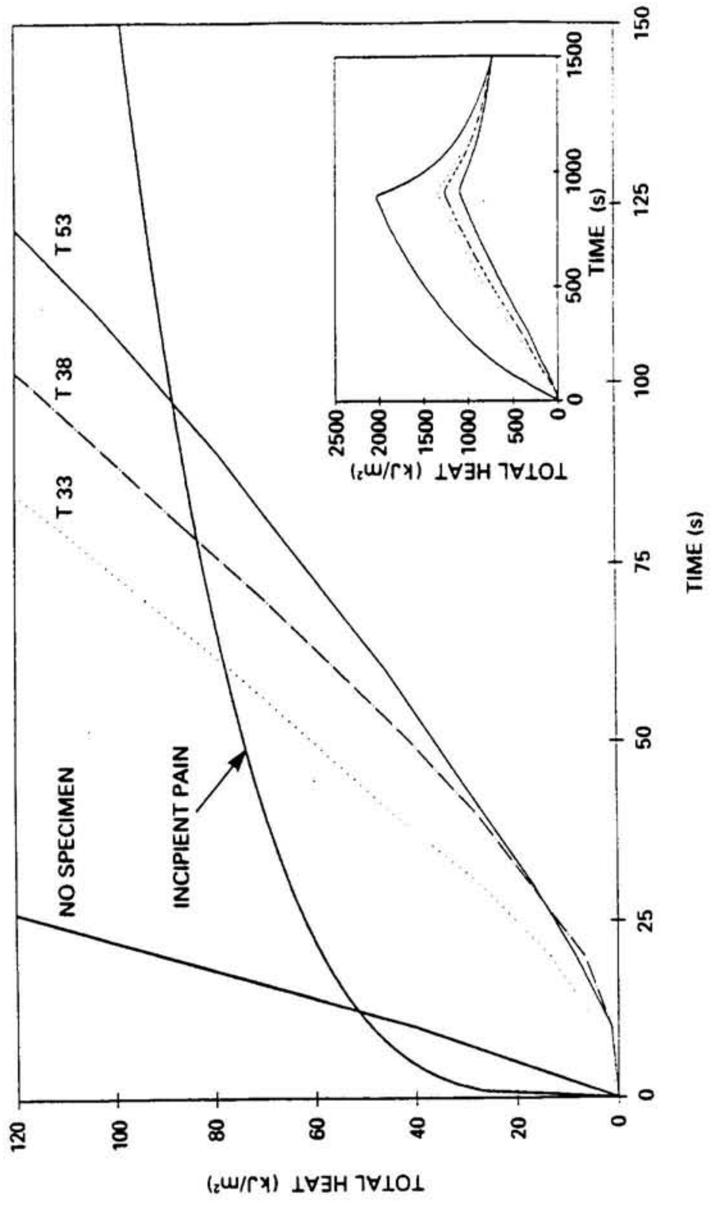

Figure 5. Total heat measured by the TPP sensors during a 500 kW gas burner fire with an open doorway.

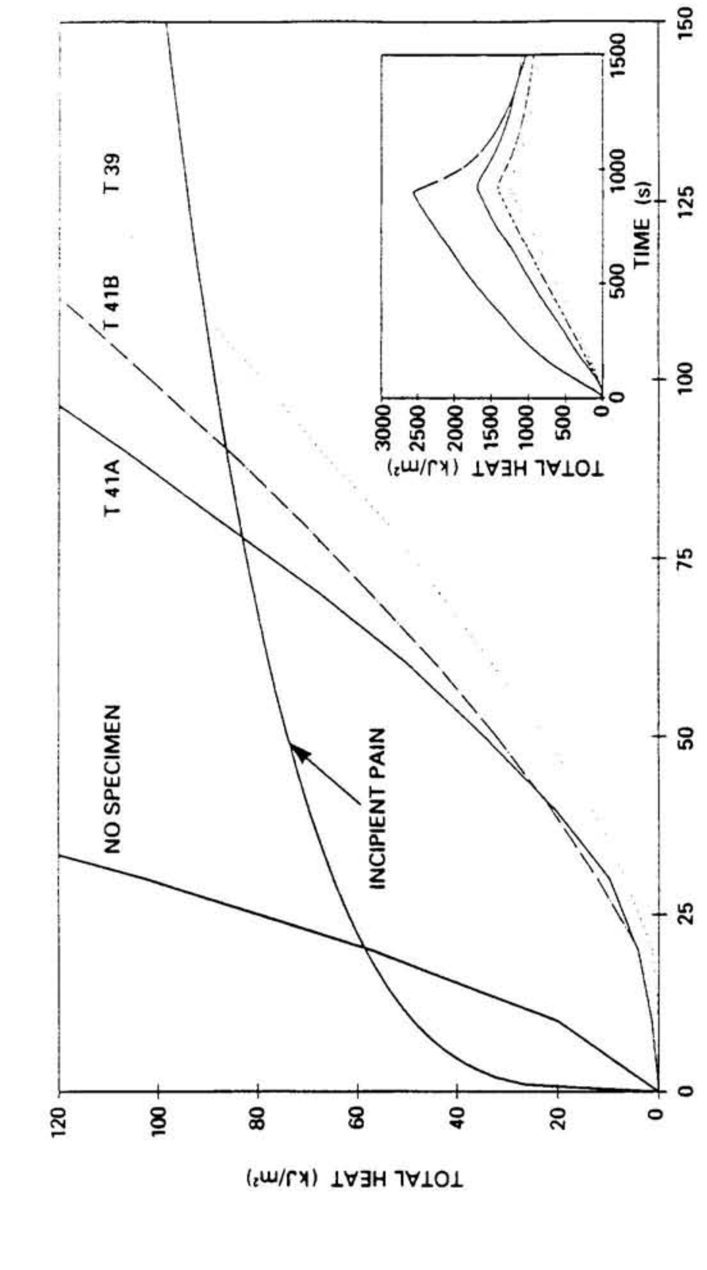

Figure 6. Total heat measured by the TPP sensors during a 500 kW gas burner fire with a closed doorway.

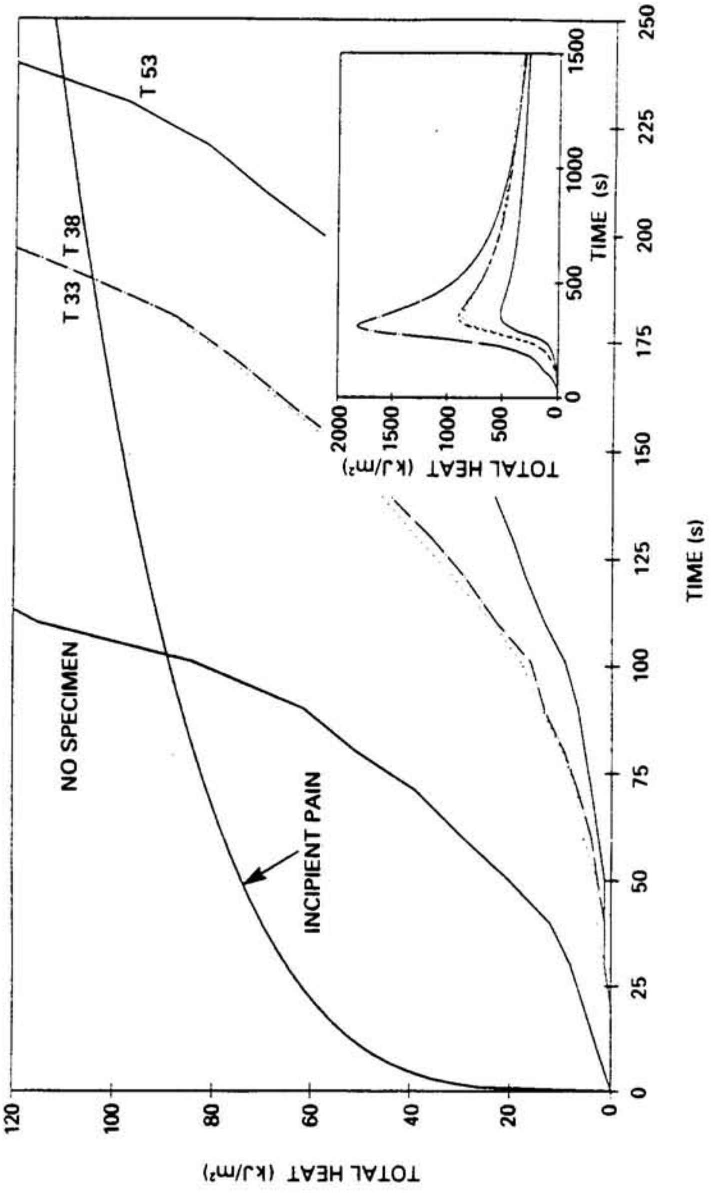

Figure 7. Total heat measured by the TPP sensors during a loveseat fire with an open doorway.

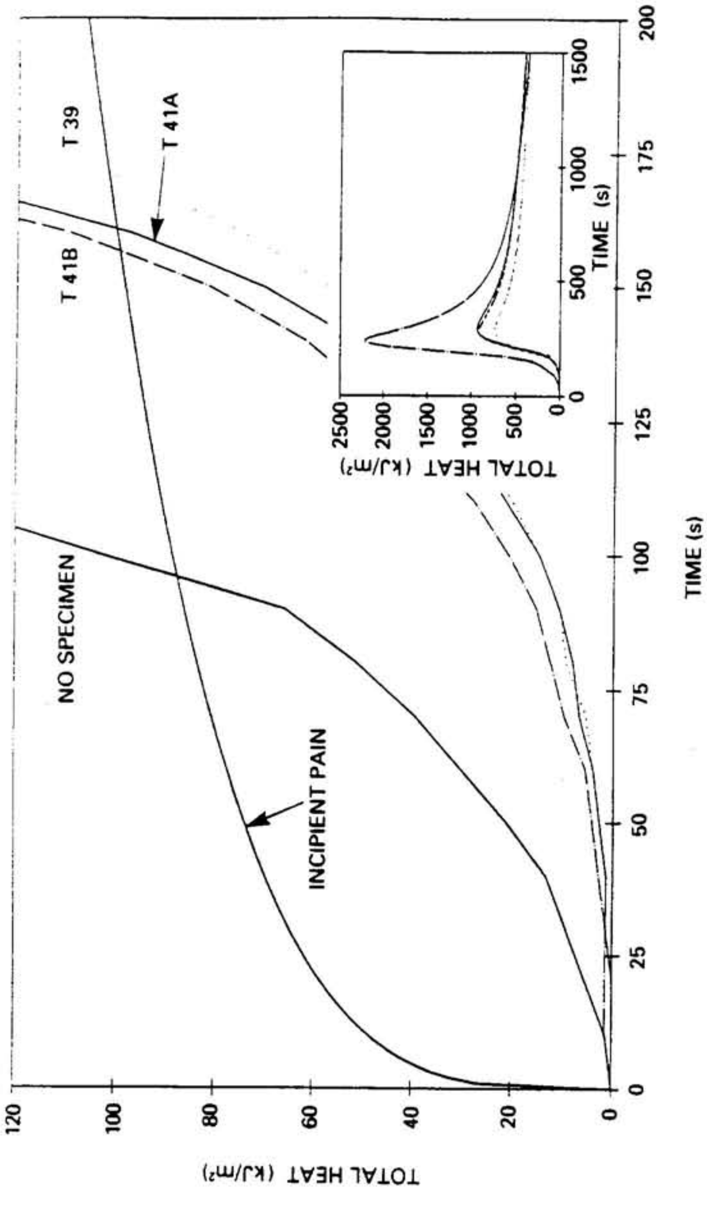

Figure 8. Total heat measured by the TPP sensors during a loveseat fire with a closed doorway.

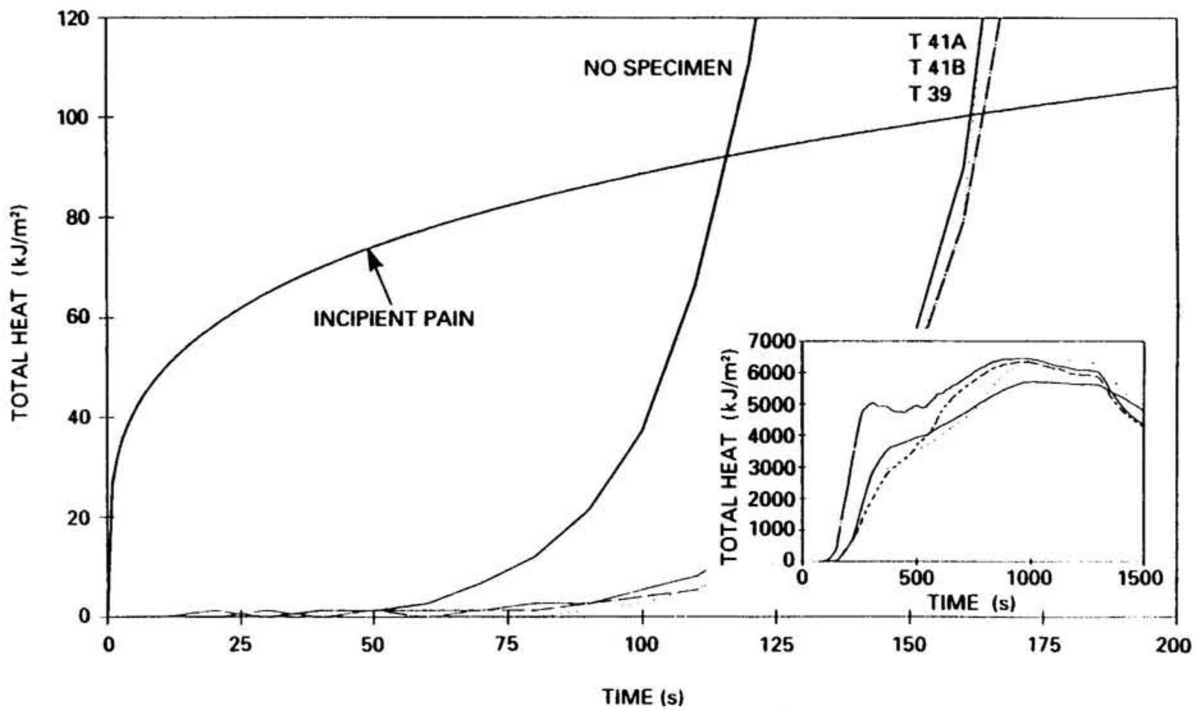

Figure 9. Total heat measured by the TPP sensors during a fully furnished room fire with an open doorway.

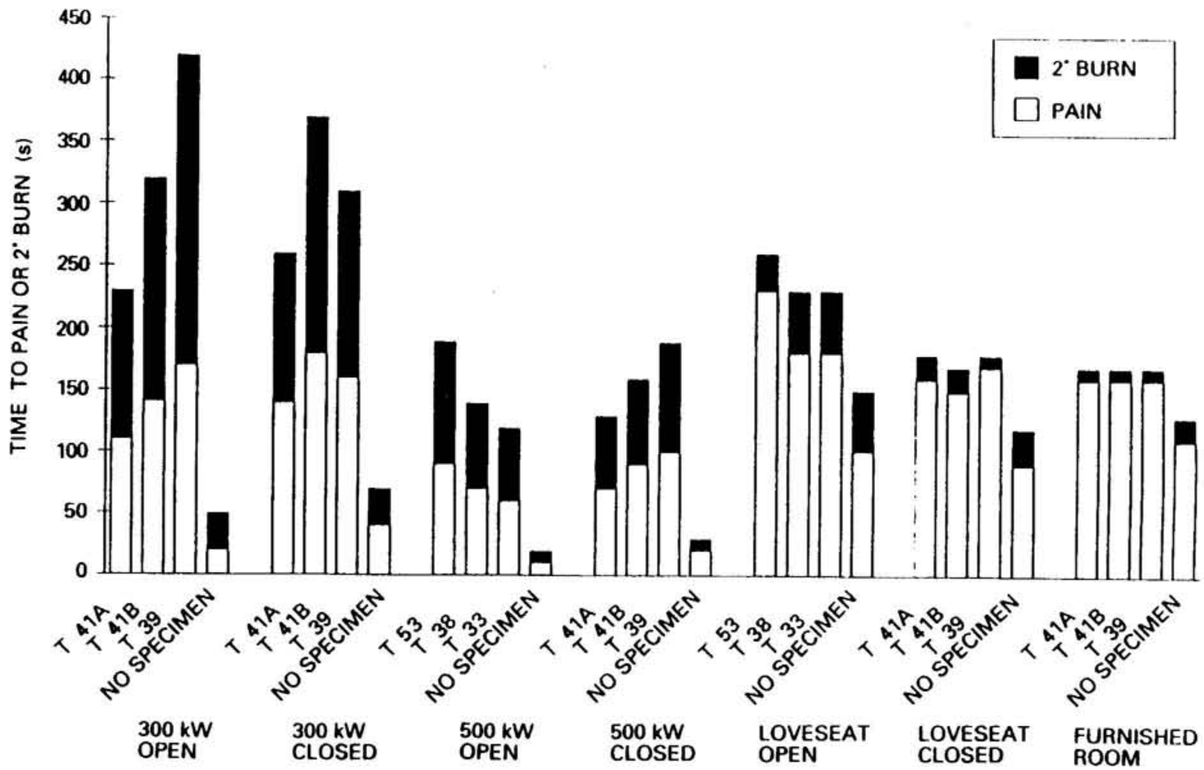

Figure 10. Estimated time to pain and 2° burn for six different turnout coat specimens exposed during several room fires.

the door open. The total heat peak was wider and lower with the door open. The fully furnished room fire, shown in Figure 9, began to build rapidly in intensity at about 100 s; after about 250 s, there was a complicated pattern of minor peaks and valleys, presumably indicating ignition of various items in the room, till a broad peak of over 6000 kJ/m^2 was reached at about 1000 s.

Turnout Coat Specimen Behavior

The three specimens varying in TPP from 33 to 53 were exposed in two fires (500 kW gas burner and loveseat, both with the door open) (Figures 5, 7, and 10; Table 2). Under conditions of relatively rapid heat build-up as in the gas burner fire, the turnout coat assembly specimens behaved generally as predicted by the TPP measurements. The time to pain was extended tenfold in the 500 kW gas fire test when the sensor was covered by the assembly with TPP 53, eightfold by specimen 38, and sixfold by specimen 33. For the time to 2° burn, the differences between specimens were smaller. Apparently, differences in the insulative value of such specimens decreased with increased time of exposure. This is further borne out by the corresponding pain/injury times in the loveseat test, in which the initial rate of heat release was slower. Here the TPP 53 specimen still showed an advantage, but there was no difference between specimens with TPP 38 and 33. It should be kept in mind that as the fire progresses, the specimens change, to varying degrees, by charring, shrinking, and buckling and that these changes probably differ according to the rate of heating as well as heat/time exposure. This is borne out, in part, by the notes on specimen appearance after each burn given in Table 2.

No consistent superiority of one of the specimens with similar TPPs was established in the five fires. In the three gas fires, the 41A specimen, with the moisture barrier coated on the inner liner, had the shortest pain and 2° burn times. Differences in the performance of the specimens were not evident in the furnishing fires with slower initial rate of heat release. For the three gas burner tests of these three specimens with similar TPP, times to pain varied between four and nine times that for the uncovered sensors; times to 2° burn varied between three and seven times. For the two more slowly developing furniture fire tests, the degree of protection was lower, with pain and 2° burn times of roughly 150 percent of the comparable time measured by the uncovered sensor.

Turnout Coat Specimen Appearance

There were considerable differences in the appearance of the specimens after the fires, as shown in Table 2. The two 300 kW fires caused no damage to the specimens. The 500 kW fires caused discoloration of the

Table 2. Time to pain and to 2° burn injury and visual assessment of specimens exposed in room fires.

Test	3	4	2	5	7	1	6
Fire Load	Gas 300 kW	Gas 300 kW	Gas 500 kW	Loveseat	Furnished Room	Gas 500 kW	Loveseat
Door	Open	Closed	Closed	Closed	Open	Open	Open
Specimen T 41A						*Specimen T 53*	
Time to Pain/2° Burn (s)	110/230	140/260	70/130	160/180	160/170	90/190	230/260
Appearance After Exposure							
Outer Shell	no eff	no eff	VDI	charbr	destr	DI	VDI
Moisture Barrier	no eff	no eff	charbr	charbr	destr	DI,SIL	DI,SIL
Inner liner	no eff	no eff	no eff	DI,compr	destr	no eff	no eff
Specimen T 41B						*Specimen T 38*	
Time to Pain/2° Burn (s)	140/320	180/370	90/160	150/170	160/170	70/140	180/230
Appearance After Exposure							
Outer Shell	no eff	no eff	DI	VDI	destr	DI	VDI
Moisture Barrier	no eff	no eff	SDI,shr	charbr	destr	SDI	DI
Inner liner	no eff	no eff	DI,shr	DI,shr, compr	destr	no eff	no eff
Specimen T 39						*Specimen T 33*	
Time to Pain/2° burn (s)	170/420	160/310	100/190	170/180	160/170	60/120	180/230
Appearance After Exposure							
Outer Shell	no eff	no eff	VDI	br	destr	DI	VDI
Moisture Barrier	no eff	no eff	charbr	br,SIL	destr	SDI,SIL	SDI,SIL
Inner liner	no eff	no eff	SDI	DI, shr, compr	destr	SDI	SDI
No Specimen						*No Specimen*	
Time to Pain/2° Burn (s)	20/50	40/70	20/30	90/120	110/130	10/20	100/150

DI-discolored, SDI-slightly discolored; VDI-very discolored; SIL-stuck to innerliner; char-charred; br.-brittle; shr.-lateral shrinkage; compr.-compressed (lost bulk); no eff-no effect.

outer shell; varying degrees of discoloration, charring, embrittlement, and sticking to the inner liner of the moisture barriers; and the inner liner appearance varied from no change to discoloration and some shrinkage. The loveseat fires caused severe damage to all assembly layers: the outer shells were generally very discolored; the moisture barriers charred in the fire with the door closed but were less damaged when the door was open; and the inner liners lost part of their bulk and sometimes shrank in the door-closed fires, and were again less affected by the open door fire. The specimens were completely destroyed during the fully furnished room fire.

Figure 11 shows the relative protection afforded by the six different turnout coat specimens in all the fires. For each specimen in each fire, the heat received by the covered sensors was normalized by the heat received by the unprotected sensor and expressed as a percentage. The curves for all tests of one specimen were then averaged and are presented in the figure. Thus, each curve shows the average amount of heat transmitted to the sensor behind each specimen relative to the heat received by the unprotected sensors and independent of the fire exposure. With the exception of specimen T 41A, the TPP values provide an accurate ranking of protective value (the higher the TPP, the less heat transmitted to the sensor behind the specimen). Consistent with the times to pain and 2° burn, specimen T 41A performs worse than predicted by its TPP value. The unique construction of specimen T 41A may account for the anomaly: It is constructed of only two layers. For fires that grow more slowly than the square wave fire simulated by NFPA 1971-1986, the protection provided by greater thickness may be of less value than the additional air space in the three layer specimens.

Summary and Conclusions

Seven fire tests were conducted in a simulated townhouse that was instrumented for measurement of heat, smoke, and pyrolysis product concentration. During these tests, six different fire fighters' turnout coat assemblies (consisting of an outer shell fabric, a moisture barrier, and an inner liner [thermal barrier]) were exposed to fires varying in intensity and the heat dose behind the coat assembly recorded. The time/heat flux curve was related to time to pain and time to incipient 2° burn injury. All but one assembly passed the heat protection requirements of NFPA 1971-86 (i.e., a TPP of 35); the range of thermal protective performance was 33 to 53.

The results of the tests of the turnout coat specimens showed:

1. All assemblies provided protection against the heat developed in these fires. Estimated time to pain for the assemblies ranged

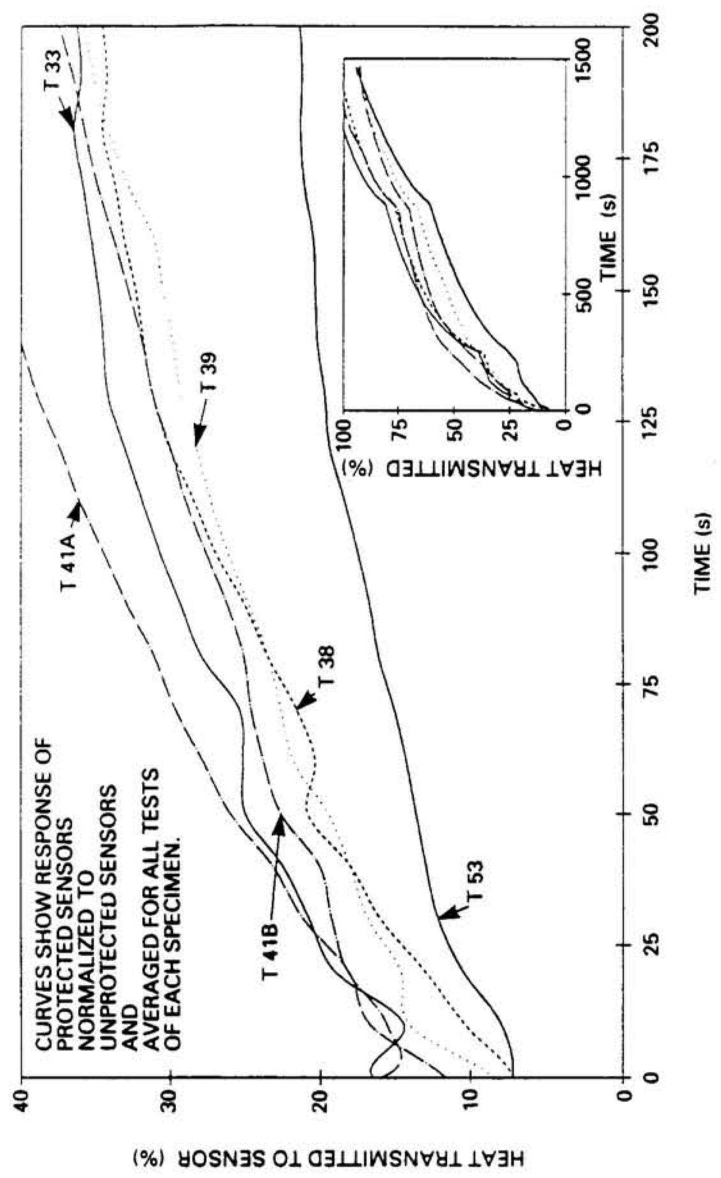

Figure 11. Average protection afforded by six different turnout coat specimens exposed during several room fires.

between 50 and 150 seconds longer than time to pain for uncovered sensors; for time to 2° burn, this range was 40 to 370 seconds.

2. The TPP bench-scale results are generally predictive of the relative protection afforded by the turnout coat specimens. Large differences in TPP were reflected in these full-scale results. However, for one specimen of unique construction, a poorer overall performance was noted in the large-scale tests than would be expected from its TPP rating.
3. Thickness does not appear to be an accurate measure of protection. For example, specimens T 53 and T 39 were of similar thickness, and also the thickest assemblies; when the data are normalized by expressing the protection times in terms of the percentage of the total incident heat (Figure 11), T 53 was clearly superior to T 39.
4. TPP results appear to be most predictive of protection afforded by various turnout coat assemblies in rapidly developing fires. These heat exposures would be typical of those prevailing when a fire fighter enters a room which is building up to flashover. Differences in TPP were less important during exposure to slowly developing fires.

The difference between the estimated time to 2° burn and time to pain can be considered an indication of "escape time," i.e., the time a fire fighter has between perception of heat on the inside of his turnout coat and the time when enough heat penetrates for a burn injury. This time ranged from 10 s to 250 s, depending on the rate of heat release of the fire. It should also be noted that these times only apply when there is direct contact between the turnout coat and the skin, and may be extended by additional layers of clothing.

These experiments indicate the value of exposing heat-protective materials in real fires to verify the results of the bench-scale TPP tests. They also suggest additional experiments, as follows: time/heat flux conditions expected to occur in a variety of situations possibly encountered by fire fighters should be duplicated in controlled tests. Besides varying levels of maximum heat flux, there should be variations in the rate of heat release, from low initial rates as seen in the loveseat fires to flashover or backdraft conditions. (A variety of conditions in room fires on which to base such experiments are recorded in many reports by the U.S. Center for Fire Research and others.) Specimens varying widely in TPP and construction should be exposed to these heat conditions for times varying from a few seconds to as much as five minutes, using water-cooled shutters to expose the specimens at various stages of a fire and thus simulate conditions encountered by a fire fighter entering or leaving a burning room. The heat behind the specimens should be measured during the exposures and for a few minutes afterwards to establish the effect of heat stored in the assemblies. The degree to which the present TPP test sample mounting is representative of the actual turnout coat use should be considered. Tests might include tensioning of the fabric sample, or periodic or continual flexure of the sample during exposure. Such experiments could further illustrate the value of the TPP specification as well as the effect of possible improvements in the turnout coat assemblies, such as charring of sacrificial layers, intumescence, buckling, etc. This type of information would be helpful in designing turnout coats for the optimum balance between heat protection on one hand and their undesirable physiological effects, due to their weight and bulkiness, on the other.

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